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Vision-based virtual force guidance for tele-robotic system ☆

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ABSTRACT

In order to improve operator performance and understanding within remote environment, a vision-based virtual forced guidance control methodology for tele-robotic system is presented. The remote operation of the construction robot is achieved by manipulating the graphic robot in a virtual environment. Based on binocular vision, the ground surface is modeled as an elevation map, and the task objects are recognized from video images and reconstructed using the Power Crust algorithm. The virtual guidance forces consisting of a pair of attractive force and repulsive force from the objects and obstacles are used to enhance the multi-task manipulation of the tele-robotic system.

1. Introduction

Tele-operation technologies have been widely used in tele-robotic systems in hazardous environments, such as outer space, deep oceans, and nuclear plants. In conventional remote operation systems, there are limitations on the number of installed sensors and the volume of transmitted data. As a result, limited information is available to the operator on site and the task efficiency is significantly influenced [1,2].

Virtual reality technology provides operator with the intuitive cue for the perception of the working fields at the remote site, which could potentially enhance the system with greater efficiency and facility [2]. Moreover, it provides the operator with a “live” virtual representation of the scene instead of the delayed video images [3]. For example, Qingping Lin introduced a virtual tele-presence interface operation approach, which greatly improved the efficiency of tele-presence operation of underwater robots by providing the operation with a 3-D virtual representation of the underwater environment [4]. However, the virtual environment is commonly built upon a “beforehand” modeling method with hypotheses that the position, size and contour of task objects have been known in advance. Besides, the operator has to judge the relative posture between the end-effector of robot and the task object with vision-only information. It is not applicative for unstructured environment and increases the operator’s workload and stress.

Force or haptic feedback is proved to be a valid method for improving the safety and efficiency of tele-robotic system [5]. As psychophysiology reveals that tactile stimulus incorporated with vision data brings about faster response time compared to vision-only stimulus [6,7], many more studies on vision-force hybrid servoing and impedance control strategy show the trend of incorporating haptics and vision with manipulation. However, in these cases, the high cost of force sensors plays critical roles, and the direct relationship between visual data and haptic force is less studied [6]. Moreover, the direct force signals which have time delay and noise in transmission are only generated when the robot interacts with the environment [8–10]. According to the feedbacks of tele-operation, operators are more concerned about the relative posture between robot and environment. The force sensors could not provide valid information under the free-moving phase of robot. A virtual collision-preventing force was generated according to the relative position between robot gripper and the environment

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obtained with a trinocular camera [11,12]. Similarly, haptic feedback was computed from the range information obtained by a sonar array attached to the robot, and delivered to an operator's hand via a haptic probe [13,14]. However, in those mentioned methods the haptic feedback was mainly used for collision prevention, instead of improving operational efficiency of tele-robotic system.

To improve the operational safety and efficiency of tele-robotic system, a force guidance control methodology is presented in this paper. The visual data captured by a binocular vision system is utilized not only for generating the virtual environment of working fields in real time, but also for providing the operator with force guidance data which includes the attractive force from the task object and the repulsive force from the obstacles. The human decision-making, the safety and the manipulation performance of tele-robotic system are improved by combining visual data with the virtual force feedback.

The rest of the paper is structured as follows: in Section 2, we describe structure of tele-robotic system with force guidance, involving a bilateral section–master and slave. Then we describe the 3-D reconstruction of task object and ground surface by the stereo vision camera in Section 3. Based on the artificial potential field theory, Section 4 shows the Generation of guiding forces, including the attractive force from task object and repulsive force from obstacles. In Section 5, comparison experiments are shown under the circumstances of force guidance and other situations. Finally, Section 6 concludes the paper.

2. Architecture of the tele-robotic system with force guidance

Fig. 1 shows the block diagram of the tele-robotic system with vision-based force guidance. The system involves a bilateral master and slave. The master is controlled by an operator and mainly consists of two force feedback joysticks and a screen with computer graphics (CG). For force feedback joysticks, Microsoft SiderWinder2 force feedback joysticks are adopted, which are capable of delivering around 100 different forces and 16 programmable buttons (8 action buttons plus 8-direction hat). The slave is composed of a construction robot and a stereo vision camera called "Bumblebee". The construction robot has four hydraulic actuators controlled by four servo vales through a control computer (PC1), and the "Bumblebee", which is a calibrated camera system as a product of Point Grey Research Inc., is mounted on top of the robot and its optical axis is perpendicular to the floor. This camera provides real time stereo image capture for applications such as tracking, building virtual reality model, human machine interface and mobile robotics. It can accurately measure the distance of the robot to the object in its field of view at a speed of up to 20 frames per second.

By means of the stereo camera "Bumblebee", the task objects in images are recognized and their contour information is extracted with a feature point based on stereo matching algorithm. Moreover, the terrain's height information of working field is also calculated according to the dense stereo matching results of binocular vision. Therefore, the task objects and the terrain are able to be rendered in the 3-D virtual environment on a graphic computer (PC2) with this information.

The operator performs remote operation of the construction robot by the joysticks with the assistance of the 3-D virtual scene in front. Operational signals for the servo valves of the robot are then generated by PC1 which processes the operational information from the joysticks. The displacements of hydraulic cylinders of the robot are detected by on-site displacement sensors mounted to hydraulic cylinders of the construction robot and input to PC2, inducing the corresponding movement of the graphic robot in the virtual world. With the information of the relative posture between robot and environment, the virtual forces, including the attractive force from the task object and the repulsive force from the obstacles or ground surface, are calculated in PC2 and fed back to the operator. With the assistance of these forces, the operator is able to control the robot approaching target quickly and avoiding collision with obstacles automatically.

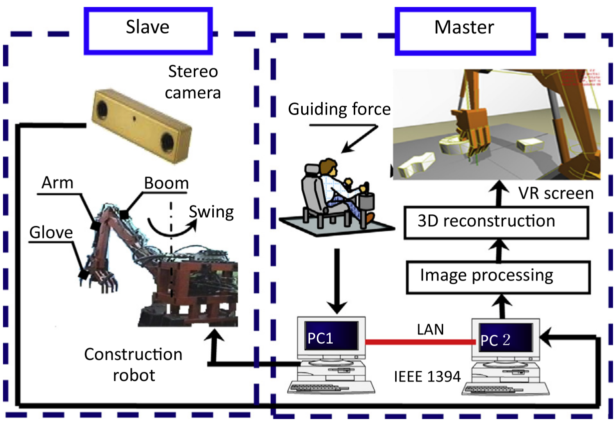


Fig. 1. Construction tele-robotic system with force guidance.

3. Vision-based 3-D reconstruction

In this system, the stereo camera "Bumblebee" has a built-in vision processing unit and is able to perform fast coordinate calculation for given pixels in the camera image. To extract 3-D positions with stereo vision, two key tasks are involved: (1) Identify the corresponding pixel in the image from one camera for a given pixel in the other camera. (2) Determine a ray in the 3-D space associated with each of the corresponding pair of pixels. In this paper, the camera is built upon a pin-hole image model, which is accurate enough for distance measurement. In order to improve the calibration of the cameras, a feature in the image captured by one camera is required to lie along a straight line in the other image.

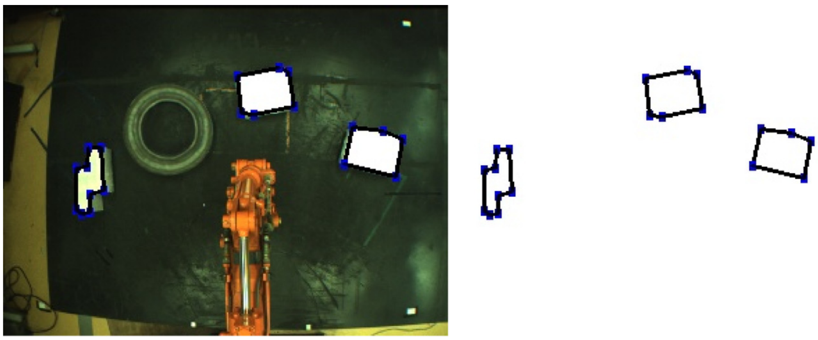
The virtual environment is developed with the open source OpenGL library in Visual C++. It aims to simulate the movement of robot and reconstruct the 3-D shape for task objects in VR world. It also provides the operator with the graphic interface for the accomplishment of tele-operation task. To build and maintain the coordinate relationship between each moving part of the graphic robot, a scene-graph representation is adopted, in which each joint is treated as a graphic entity node and attached to its parent node in a tree structure. The movement of parent node will cause the corresponding movement of all of its child nodes. During the simulation, all nodes in the scene are traversed and updated in every frame.

3.1. Reconstruction of task object

The 3-D reconstruction of the task object is based on the Power Crust algorithm [15], which guarantees to produce geometrically correct approximations of the objects even when the sample points fail to be sufficiently dense [16]. The idea of the Power Crust is that the medial axis transform (MAT) of the object is first approximated with a set of samples. The MAT estimation is a subset of the Voronoi vertices called poles. The object approximation is then obtained with a set of finite polar balls centered on each pole of the estimated MAT, with the radius corresponding to the weight of the pole. The object surface could be produced from the diagram of weighted poles.

To concentrate on the generation of guiding force, obvious differences in the color, grayscale and texture between task object and ground surface are supposed in the system. The procedure of recognition and 3-D reconstruction of task objects are demonstrated as follows:

(1) A "Bumblebee" camera captures a video image (as shown in Fig. 2(a)) in its field of view and measures the distances to task objects.
(2) Generate the binary image B_{obj} for the task objects region and the binary image B_{rob} for the robot shadow region by applying color, texture, and height threshold to the input images.
(3) Dilation and erosion methods are applied on the binary image so as to eliminate very small holes caused by camera noise.
(4) Make labels i ($i = 1, 2, 3\ldots$) for the isolated regions on the B_{obj} and remove small area region whose size is little than 10×10 cm; Also, make labels j ($j = -1, -2, -3\ldots$) for the B_{rob} and only keep the labeled regions with maximum area.
(5) Incorporate the B_{obj} and B_{rob} into one binary image, in which the task objects region could be distinguished from the robot shadow region by their positive or negative labeling values.
(6) Extract the contours C_{obj} and C_{rob} for the task objects region and the robot shadow region respectively through the point splitting and merging algorithm, as shown in Fig. 2(b).
(7) The C_{rob} region is treated as polygon and used to detect whether the task objects are hidden by the robot or not, based on the collision information between the C_{rob} polygons and the C_{obj} polygons. If the task object is hidden, then the image feature of C_{obj} is retrieved from previous frame.



(a) Camera image (b) Contour points

Fig. 2. Recognition of working field.

Fig. 3. 3-D shape of task object.

(8) The coordinates of all the points within C_{obj} region are calculated, and their 3-D point clouds are generated. With the input of these point clouds, the surface of the task object is obtained through the Power Crust algorithm, as shown in Fig. 3.

All the task objects in the virtual world are assigned with certain characteristics of mass, density, friction, etc. and expected to obey the Newton's physics principle. In order to reduce the computational complexity, the objects in current VR application are treated as rigid bodies and no deformation is occurred during the simulation. The dynamic interaction between virtual objects and graphic robot is realized by Nvidia PhysX SDK 2.8.3. When the task object in image is partially hidden by the robot, its dynamic behavior in VR is determined by the physics principle. Otherwise, the position of task object is calculated based on the steps above and updated in real-time.

3.2. Reconstruction of ground surface

The "Bumblebee" camera provides real-time range images based on stereo vision technology, which allows users to accurately measure the distance to every valid pixel in an image and to generate depth map fast and accurately.

The ground surface is represented by an elevation map coincident with the x–y plane of the voxel grid [15]. The height of a cell in the elevation map is set to the average height of the points found in the bottom-most occupied voxel in the voxel array above that cell. The camera image and the calculated elevation map are shown in Fig. 4(a) and (b), respectively.

Due to the potential failure of the pixel matching process, some height map cells may not have any measurement value. Therefore, a linear interpolation algorithm is applied across gaps smaller than a configurable number of cells in X and Y directions to fill small holes [17].

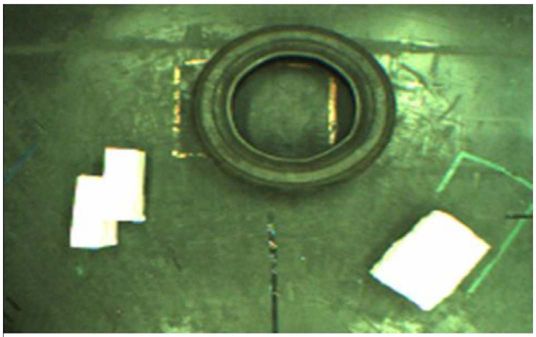
Like other approaches based on stereo matching, the "Bumblebee" may fail to produce correct 3-D points along the discontinuities on a surface. This problem becomes more noticeable when parts of working field or task object were hidden behind the robot. A 5×5 Gaussian filter or a 5×5 square mask median filter was applied for the low-pass operation to prevent sharp transition of distance in the depth map. Further, in order to enhance the realistic appearance of the ground surface and provide operator with more detailed visual cues, a texture is mapped to the elevation map cells with the video imagery.

4. Generation of guiding forces

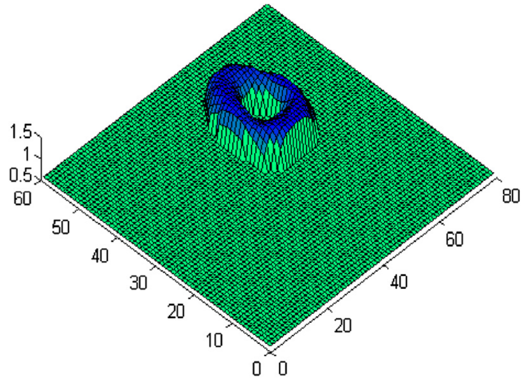
In the conventional bilateral servo system, the tele-operative manipulation is usually performed with force feedback, which could considerably improve the user's ability to perform complex tasks. However, the contact force detected from sensors only exists when the robot collides with environment. Under certain conditions, especially in a high-speed or heavy-load robot system, an instant contact between environment and robot could result in serious consequences. When the robot moves freely and no collision occurs, the control strategy of force feedback would lose its role since the force sensors could not provide valid information in this case.

In order to improve the safety and manipulation performance of tele-robotic systems, a vision-based virtual force guidance methodology is presented in this paper. The virtual forces, which include the attractive force from task object and repulsive force from obstacles, are built upon the recognized images of working fields using binocular vision technique rather than generated from the force sensors. Consequently, the kinesthesia is generated from the virtual forces as the haptic cue and transmitted to the operator by joysticks.

According to the artificial potential field theory, which was first proposed by Khatib [18] and originally developed for an on-line collision avoidance [19–21], there must exist one path that can lead the robot move towards the target and avoid obstacles automatically in the virtual potential field. Therefore, it is possible to develop the relationship between the virtual force and the potential function, which is the key part of the new force guidance strategy.



(a) Image of ground surface



(b) Calculated height map

Fig. 4. Reconstruction of ground surface.

The robot moves under the influence of an artificial potential field V defined as the sum of an attractive potential V_G pulling the robot towards the goal configuration γ_* and a repulsive potential V_O pushing the robot away from the obstacles. An artificial force $F(\gamma)$ defined as $F(\gamma) = -\vec{\nabla}_\gamma^T V$ could ensure that the robot reach a global minimum in the potential field, where γ is the vector that identifies the pose of the end-effector of a robot in the extrinsic workspace, and $\vec{\nabla}_\gamma^T V$ denotes the transpose of the gradient vector of V at γ.

In this approach, the attractive potential field V_G is simply defined as:

$$V_G(\gamma) = \frac{1}{2}(\gamma - \gamma_*)^2 \tag{4.1}$$

where γ is the vector that identifies the pose of the end-effector of a robot in the extrinsic workspace, and γ_* is the goal configuration of robot.

The function V_G is positive or null and attains its minimum at γ_*. Based on the artificial potential field theory, the attractive force F_G could be generated as:

$$F_G = -(\gamma - \gamma_*) \tag{4.2}$$

The repulsive potential V_O is defined as:

$$V_O(\gamma) = \begin{cases} \frac{1}{2}\eta\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right)^2 & \rho \leqslant \rho_0 \\ 0 & \rho > \rho_0 \end{cases} \tag{4.3}$$

where ρ represents the distance between the obstacle and the end-effector of robot along its velocity direction, ρ_0 denotes the influence distance of this potential field. η is a constant which determines the magnitude of repulsive potential.

The function V_O is positive or null and reaches to a maximum at the boundary of the obstacle, but it will reduce to zero when the robot is sufficiently away from it. The repulsive force F_O could be generated as:

$$F_O = \begin{cases} -\eta\left(\frac{1}{\rho} - \frac{1}{\rho_0}\right)\frac{1}{\rho^2}\vec{v} & \rho \leqslant \rho_0 \\ 0 & \rho > \rho_0 \end{cases} \tag{4.4}$$

where $\vec{v}$ is the normalized velocity vector of the end-effector of robot.

In this system, the task object is laid on the ground surface, and its oriented bounding box (OBB) that is a rectangular bounding box at an arbitrary orientation in 3-space and is able to enclose an object more tightly, as is oriented to the lie of the object [22], could be calculated based on the 3-D reconstructions in VR. The most subvertical axis of OBB is selected as the target orientation of the end-effector of the robot. Along the axis, the point with a distance of $(l_0/2 + d)$ to the center of OBB is selected as the target position, where l_0 is the length of OBB, and d is a constant. In addition, a ray is sent out along the velocity direction of the robot's end-effector in the virtual environment and its distance to obstacles or the intersection points of the ground surface could be measured by the function interface of PhysX SDK.

The guiding force feedback to the joystick is given by:

$$F_m = \alpha F_G + \beta F_O + F_e \tag{4.5}$$

where the scaling factors α and β are allowed to adjust the relative influence of the different virtual forces, F_e is the contact force between robot and environment detected from force sensors.

Considering the importance of the attractive force F_G, it is critical to achieve an acceptable measurement accuracy of the vision system about the position of task object. As shown in previous research testimony, in the 1024×768 resolution, the detection error of the vision system is less than 4 mm when the object is 2 m far from Bumblebee camera. Furthermore, this detection error approaches the index-diminishing with the decrease of the distance. Therefore, the measurement accuracy of Bumblebee could assure that the successful information is transferred from the workplace to the virtual force in the process.

During the free-moving phase of manipulation, the effect of the attractive force is the equivalent of adding an elastic band between the target and the end-effector of robot, while the result of repulsive force is just like putting virtual springs along the velocity direction of the robot. With the assistance of the virtual forces, the operator could manipulate the robot approaching the target quickly and avoiding obstacles automatically simultaneously. When the end-effector reaches its target position and starts to grasp the object, the virtual guiding forces will become zero and the operator will feel the real grasping force.

5. Experimental result

In experiments, operators performed specified tasks by operating the construction robot by the joysticks. The construction robot is located in the static environment which is unknown beforehand. By the approach discussed in Chapter 3, the 3-D virtual environment was generated. The operator manipulated the on-site robot by the joysticks with the assistance of the 3-D virtual environment. At the same time, the operator received the feedback information from the on-site robot, which caused the corresponding movement of the graphic robot. In the first set of experiments, as shown in Fig. 5, the operator manipulated the robot from the starting point in which the robot was located initially to target object in area C, which involves some simple obstacles in the working fields, and the following manipulation methods were executed.

(1) Method one: manipulation in the virtual environment without the force guidance.
(2) Method two: manipulation in the virtual environment with the force guidance.

Fig. 6 shows the relative distance between the task object and the end-effector of the robot during tele-operation. The abscissa shows the time of the movement, and the ordinate shows the distance in the corresponding time. Fig. 7 plots the paths that the robot moves from the start point to the final destination. The red dashed line represents the path under the manipulation method one, while the black solid line represents the path under the manipulation method two.

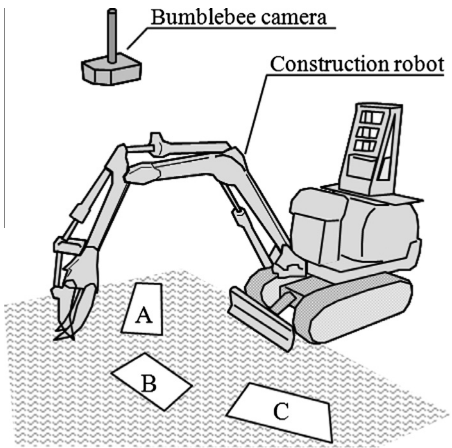


Fig. 5. Task area for evaluation of operation.

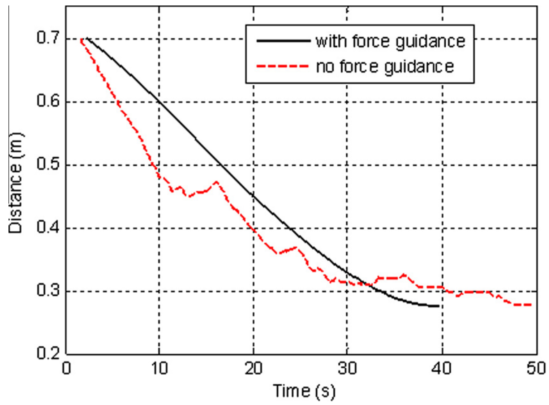


Fig. 6. Distance between the end-effector of robot and the target.

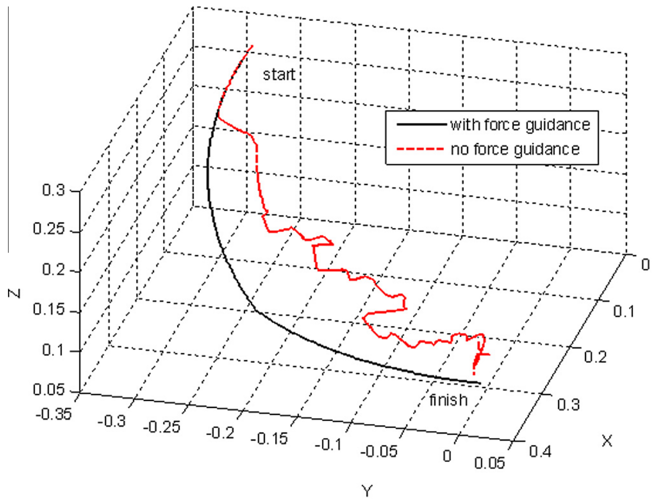


Fig. 7. Motion path of robot toward target.

As shown in Fig. 6, force guidance control methodology can significantly shorten the operating time of task accomplishment during VR assisted tele-operation. The virtual environment could provide the operator with distinct recognition of working fields. However, parts of the distance information may be lost when projected onto a 2-D display. Therefore, the operator still needs to judge the relative position and orientation between robot and task object in the 2-D image.

In addition, considering the big difference between the master manipulator and slave robot on the aspects of structure, size and manipulation space, it is necessary to regulate many times the control commands due to the lack of experience and feed-back information during manipulation, as is shown in Fig. 7. As a result, the working efficiency of tele-operation is reduced, and the psychological stress and the fatigue of decision-making are increased. By introducing guiding force into the VR assisted tele-operation, the relative position between the robot and the task object is fed back to the operator in terms of force and haptic hint, which is significantly beneficial to the operator when manipulating the robot approaching the target effectively, rapidly, smoothly and safely.

Fig. 8 plots forces generated on joysticks. The abscissa shows the time of the movement, and the ordinate shows the respective force on joysticks in the corresponding time. The F_{1x}, F_{1y}, F_{2x} and F_{2y} represent two-dimension forces on joysticks respectively (see Fig. 8).

While the end-effector is approaching the target, the guidance forces, which include the attractive and repulsive forces, are generated directly based on visual data to pull or push the operator to make the end-effector approach the target rapidly and avoid obstacles automatically. When the robot is located in the initial position in which is far from the target, the virtual guidance force is larger and is capable of providing the operator with a stronger sense of touch. As the robot approaches the target, the forces tend to become zero.

In the second set of experiments, the tele-operation task involved the transportation of objects from one place to another, as shown in Fig. 5.

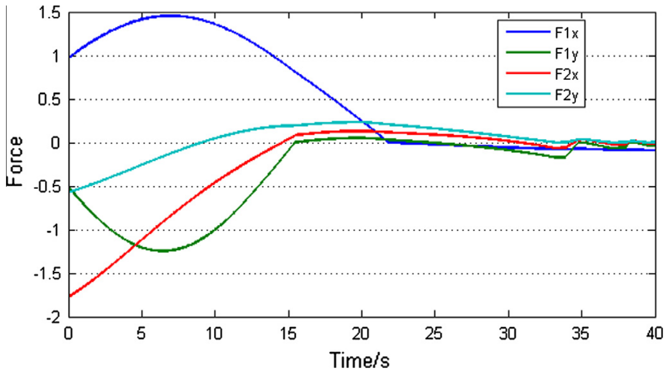
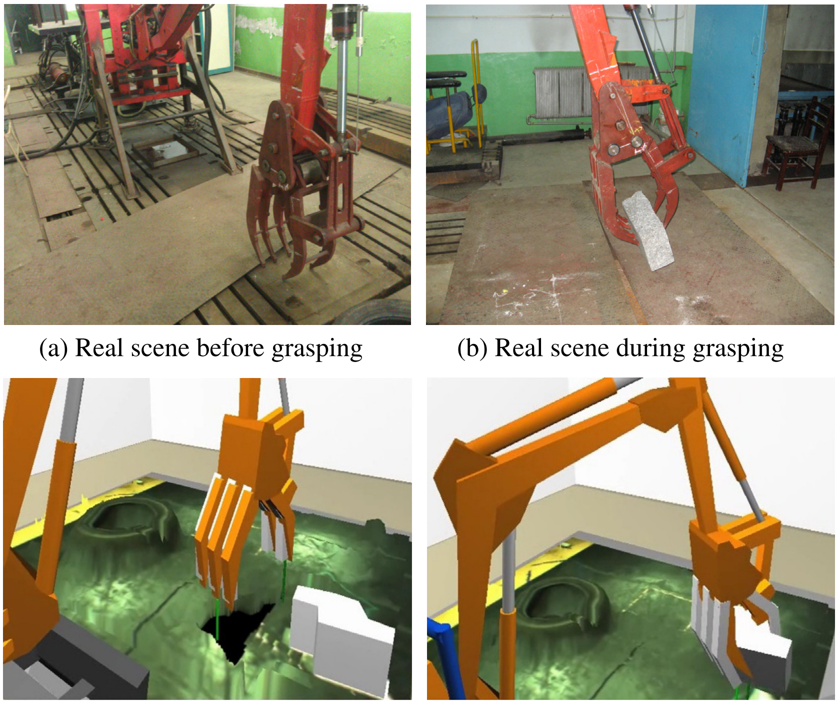


Fig. 8. Forces generated on joysticks.



(a) Real scene before grasping (b) Real scene during grasping

(c) VR scene before grasping (d) VR scene during grasping

Fig. 9. Scene of experiments.

Task:

(1) One block is put at B and C respectively.
(2) Block at C is transported to A.
(3) Block at B is stacked on top of the block at A.

Experiments were carried out under three various conditions, one is with the VR plus assisted guiding force, one is with the VR only, and the other is with image feedback only. The real and virtual scenes for manipulation task are shown in Fig. 9. The time which is required to complete the task under each condition, the time and the contact force between the construction robot and the ground surface are measured.

Fig. 10 shows the average number of block movements that the tele-operation tasks completed in one minute. The abscissa shows the conditions of experiments, and the ordinate shows task efficiency (objects/minute). Larger values on the ordinate indicate higher task efficiency. With the assistance of guiding force and VR environment, the task efficiency increased by approximately 40% in comparison with the VR-only method, and almost three times that of image-only method. This is mainly because human is more sensitive to force or haptic hint than visual hint. With the virtual force guidance, the

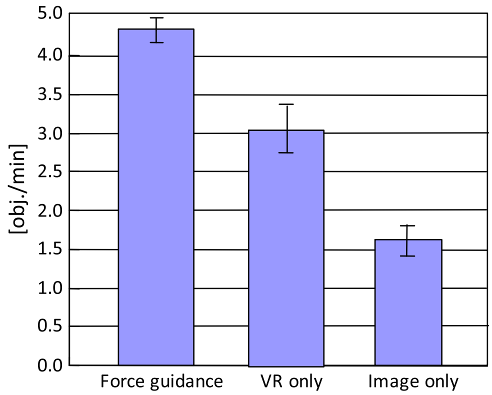


Fig. 10. Experiment of efficiency.

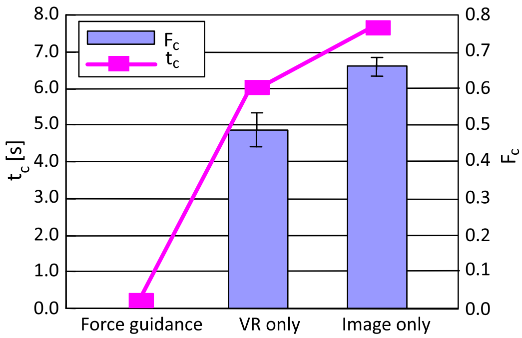


Fig. 11. Experiment of risk measurement.

operator does not need adjust the end-effector of the robot redundantly when approaching the target object. In the meantime, the operator could change his viewpoint dynamically to achieve the best view position and to avoid being hidden by the robot arms with the help of the virtual environment.

Fig. 11 shows the average time and contact force between the construction robot and the ground surface. The abscissa shows the conditions of experiments, and the left ordinate shows the time of contact with the floor, e.g. tc in seconds, while the right ordinate shows the dimensionless force F_c obtained from the average force of the boom, arm, and swing. On both the right and left axes, larger values indicate more dangerous. It is obvious that the VR plus force guidance method has absolute superiority in safety among all. With the introduction of virtual repulsive force from obstacles, the robot could be pushed away before collision with the environment. However, with 2-D image feedback only, the operator feels difficult to judge whether the robot have contacted with the ground or not, which leads to a higher danger coefficient during the operation.

6. Conclusion

As robots play more diverse and important roles in our daily lives especially in hazardous environment, an effective interaction between human and robots as well as appropriate training methods concerning the safe operation of the robots will be required. In this paper, we present the effective way of guiding human operator in tele-manipulative tasks by the means of virtual force guidance and virtual reality technology. First we have introduced this new approach with respect to the correlation between the control force and the virtual force which includes a pair of attraction force from target objects and rejection force from obstacles. Then a virtual reality environment is established to couple with the virtual force guidance to enable ease-of-use for human operators performing common manipulation activities. By integrating the machine intelligence and human decision, the force guidance control methodology enhances the mixed-initiative tele-operation and semi-autonomous control of robotic manipulators.

Experimental results show that the methodology improves the tele-operation performance with respect to efficiency, safety, and stress reduction.

Acknowledgments

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